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RESEARCH MEMORANDUM

EFFECT OF DISTRIBUTED GRANULAR-TYPE ROUGHNESS ON BOUNDARY-LAYER TRANSITION AT SUPERSONIC SPEEDS WITH AND WITHOUT SURFACE COOLING

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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EFFECT OF DISTRIBUTED GRANULAR-TYPE ROUGHNESS ON BOUNDARY-LAYER TRANSITION AT SUPERSONIC SPEEDS WITH AND WITHOUT SURFACE COOLING

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SUMMARY

An investigation was made in the Langley 4- by 4-foot supersonic pressure tunnel at Mach numbers of 2.01 and 1.61 to determine the effect of a distributed granular-type roughness on boundary-layer transition for the model surfaces at equilibrium temperature and at values of the temperature considerably less than equilibrium. Velocity fluctuations in the boundary layer were observed by means of a hot-wire anemometer. The transition-triggering mechanism of the three-dimensional roughness at supersonic speeds appeared to be the same as that previously observed at subsonic speeds. In fact, the critical value of the roughness Reynolds number parameter $\sqrt{R_{k,t}}$ (i.e., the value at which turbulent "spots" are initiated by the roughness) was found to be approximately the same at supersonic and subsonic speeds when complete local conditions at the top of the roughness, including density and viscosity, were considered in the formulation of the roughness Reynolds number. For three-dimensional roughness at a Reynolds number less than its critical value, the roughness introduced no disturbances of sufficient magnitude to influence transition. Surface cooling, although providing a theoretical increase in stability to small disturbances, did not increase to any important extent the value of the critical roughness Reynolds number for distributed granular-type roughness. Cooling, therefore, because of its effect on boundary-layer thickness, density, and viscosity actually promoted transition due to existing three-dimensional surface roughness for given Mach and Reynolds numbers.

INTRODUCTION

A low-speed experimental investigation of the effect of distributed granular-type roughness on boundary-layer transition as reported in

reference 1 indicated that, when the roughness is sufficiently submerged in the boundary layer to provide a substantially linear variation of local velocity with distance from the surface up to the top of the roughness, turbulent "spots" begin to appear immediately behind the roughness when a local roughness Reynolds number based on the velocity at the top of the roughness and the roughness height exceeds a value of approximately 600. These data, as well as those of references 2 and 3, for example, indicate that at roughness Reynolds numbers even slightly below the critical value, three-dimensional type roughness introduces no disturbances of sufficient magnitude to influence transition but that only a very small increase of roughness Reynolds number above the critical value is required to move transition substantially up to the roughness. This mechanism of transition is in sharp contrast with experience with two-dimensional-type disturbances (for example, full-span cylindrical wires) where transition occurs some distance downstream of the roughness and gradually moves forward to the roughness position as the Reynolds number is increased (ref. 4).

The purpose of the present experiments was to extend the investigation of reference 1 to supersonic speeds to determine whether the transition-triggering mechanism of distributed three-dimensional particles is the same at supersonic speeds as that observed at subsonic speeds and to determine the critical value of the roughness Reynolds number at the higher speeds. In addition, information on the effects of surface cooling on boundary-layer transition associated with surface roughness was desired.

It is well known from the theories of amplification of small disturbances in a laminar boundary layer that, for a "stable" laminar layer, small two- or three-dimensional disturbances will damp out as they move downstream. It is also known that either boundary-layer suction or cooling has a stabilizing effect on the laminar layer for these theoretically small disturbances. Depending upon the amount of suction (ref. 5, for example) or cooling (refs. 6 to 9), then, the transition Reynolds number based on the extent of laminar flow can be appreciably increased over the natural transition Reynolds number if the surfaces are sufficiently devoid of either three-dimensional or two-dimensional types of roughness elements. For two-dimensional roughness elements of finite size, it has been found that cooling can have a beneficial stabilizing effect in that some increase in transition Reynolds number can be obtained depending upon the value of Mach number, size of the two-dimensional roughness, and amount of cooling. (See ref. 8.) For three-dimensional roughness elements of finite size, however, reference 10 indicated that at subsonic speeds, at least, the critical value of the three-dimensional roughness Reynolds number was not greatly increased when the boundary layer was stabilized through application of continuous suction. This difference in the effect of laminar boundary-layer

stability on the initiation of turbulence caused by two- or three-dimensional-type roughness is associated with the basic difference in the triggering mechanism of turbulence that has been experimentally determined for the two types of roughness as previously described. That is, disturbances resulting from two-dimensional roughness appear to be of the Tollmein-Schlichting type and are subject to amplification theories whereas disturbances resulting from three-dimensional roughness, on the basis of low-speed experimentation, do not appear to be subject to such stability arguments. In order to determine at supersonic speeds the sensitivity to three-dimensional distributed roughness of the laminar boundary layer with increased stability, the model of the present investigation was also tested with the surfaces cooled.

The investigation was made on a 10° cone in the Langley 4- by 4-foot supersonic pressure tunnel primarily at a Mach number of 2.01 with a few tests made at a Mach number of 1.61. Various combinations of distributed roughness size and location were investigated with the cone surface at both its equilibrium temperature and cooled. Indications of the nature of the boundary-layer flow were obtained by means of a hot-wire anemometer. Only part of the results obtained in this investigation is presented herein in order to expedite publication.

SYMBOLS

k	height of projection
M_∞	free-stream Mach number
s	surface distance from cone apex
u	local streamwise component of velocity inside boundary layer
U	local velocity just outside boundary layer
ν	coefficient of kinematic viscosity
R'	Reynolds number per foot based on velocity and kinematic viscosity outside boundary layer, U/ν
R_k	projection Reynolds number based on roughness height and velocity and kinematic viscosity at top of roughness, $u_k k/\nu_k$
T_w	surface temperature, °F

Subscripts:

k conditions at top of roughness projection

t conditions at which turbulent spots appear

MODEL

A 10° cone configuration was used in the present investigation. Actually two different models were used for different phases of the program: (1) a solid aluminum-alloy cone 24 inches long and (2) a hollow, thin-walled, stainless-steel cone $25\frac{1}{2}$ inches long for the cooling tests. Although the latter model was not the most desirable for heat-transfer experiments because of the inability to attain a uniform longitudinal temperature distribution when cooled, it was used because of its availability, and it did permit attainment of valid effects of surface cooling on boundary-layer transition in the presence of surface roughness. A sketch of the hollow model presented in figure 1 includes the locations of iron-constantan thermocouples used to measure the surface temperatures and a photograph of this model is presented as figure 2.

APPARATUS AND TESTS

The investigation was made at Mach numbers of 2.01 and 1.61 in the Langley 4- by 4-foot supersonic pressure tunnel, which is a rectangular, closed-throat, single-return wind tunnel with provisions for control of the air stagnation pressure, temperature, and humidity. The appearance of transition was observed by means of a hot-wire anemometer, the output of which was fed into an oscilloscope. The wire, which was a 3/32-inch length of 0.0003-inch-diameter tungsten, was arranged to be sensitive only to variations in the u-component of velocity and was located approximately 6 inches from the base of the model. Three hot-wires were located circumferentially 120° apart at this longitudinal station in order to improve the probability of retaining a wire for the duration of a test run. These odds proved satisfactory because no runs were aborted due to loss of all three wires, although at least one wire was lost each time. Records of the hot-wire response to velocity fluctuations were made by photographing the traces on a cathode-ray tube.

Carborundum grit of various size, thinly spread over the surface in strips of about 3/16-inch width, was used as the distributed three-dimensional roughness. Closeup photographs of three representative strips are presented as figure 3. For each of the following investigated

combinations of roughness size and location along the surface from the cone apex, the roughness was submerged in the boundary layer:

Surface distance from cone apex, in.	Grit no.	Mean grit height, in.	Maximum grit height present, in.
1	180	0.0035	0.005
2	180	.0035	.005
2	80	.0083	.010
3	80	.0083	.010
3	70	.0098	.015
5	60	.0117	.023
5.9	240	.0029	.003
10.3	60	.0117	.023
10.4	80	.0083	.010
10.4	80	.0083	.011
12.5	60	.0117	.019

The height of the particles in each roughness strip tested was carefully measured with a 15-power shop microscope before and after each test run. The maximum grit height found is listed in the last column of the table.

The model was cooled by means of liquid carbon dioxide which was sprayed into the interior of the hollow model through small orifices drilled in and near the end of a $\frac{1}{4}$-inch-diameter copper tube. The tube was brought through the base of the model and was located approximately as indicated in figure 1.

The test procedure consisted of starting the tunnel at a low value of stagnation pressure and equivalent unit Reynolds number and then gradually increasing the Reynolds number to a value somewhat greater than that required for the initiation of turbulent spots behind the roughness. Photographs of the hot-wire response were taken for various types of boundary-layer flow throughout the stagnation pressure range. For the cooling tests, the model was cooled when the unit Reynolds number was adjusted to the critical point, that is, the stagnation pressure at which turbulent spots began to appear. Photographs of the change in boundary-layer character were made and then the stagnation pressure readjusted to return the flow to the almost completely laminar condition (i.e., with the occurrence of spots) at which point photographs were again taken. The distribution of surface temperature was recorded simultaneously on recording-type Brown potentiometers and a direct correlation was kept between the oscillograph photographs, potentiometer records, and tunnel stagnation pressure and temperature. For large amounts of cooling, frost

formations on the model surface initiated occurrence of turbulent spots and in some cases resulted in wire breakage, probably due to collision of ice particles with the hot wire. The data presented have been limited to frost-free conditions.

RESULTS AND DISCUSSION

A representative example of the various types of boundary-layer flow observed is given in figure 4 in the form of hot-wire traces of the time variation of velocity in the boundary layer. On the vertical scale of the figure is given the value of tunnel unit Reynolds number (Reynolds number per foot) corresponding to each trace. The points of light photographed on each trace are timing points, the spacing of which corresponds to 1/120 second with time increasing from left to right. The amplifier and oscillograph attenuations were maintained the same for all hot-wire traces taken during each test run.

Figure 4 indicates that transition is initiated in the form of infrequent disturbances of very short duration that increase in frequency as the unit Reynolds number increases. These observed changes in the character of the boundary layer with changes in Reynolds number are similar to those observed at subsonic speeds in reference 1 and are consistent with the concept of the origin of turbulence as turbulent spots that grow in size as they move downstream (ref. 11). The hot-wire traces of figure 5 also verify the indications of references 1 to 3 that for three-dimensional roughness at a Reynolds number less than its critical value, the roughness will introduce no disturbances of sufficient magnitude to influence transition. At a unit Reynolds number of 2.86×10^6, the flow was laminar for both the model smooth condition and for the model with 0.003-inch roughness located 5.9 inches from the cone apex. At a unit Reynolds number of 3.29×10^6, infrequent turbulent spots appeared at the hot-wire location for both model surface conditions, and an increase in the unit Reynolds number increased the frequency of occurrence of the spots until the flow was almost completely turbulent at a unit Reynolds number of about 4.0×10^6. Although for the same or slightly lower values of the unit Reynolds number the turbulent spots appear to occur somewhat more frequently for the rough surface condition than for the smooth condition, the differences involved are associated with such small increments in Reynolds number within the range required to change the flow from the initial formation of spots to the fully turbulent condition that it appears highly improbable that a repeat test for either surface condition could duplicate the comparisons to such a degree of accuracy. In fact, these differences are of the same order of magnitude as typical scatter in other experimental investigations of transition such as found in reference 12.

If the roughness applied to the model for the test of figure 5 had introduced significant disturbances into the laminar layer, transition would have occurred at the hot-wire location at an appreciably lower value of the Reynolds number than that required to move transition forward of that point with the model smooth $\left(3.3 \times 10^6 < R' < 4.0 \times 10^6\right)$.

Correlation of boundary-layer transition due to a randomly distributed three-dimensional type of surface roughness has been accomplished at subsonic speeds in reference 1 on the basis of a critical local roughness Reynolds number formulated with the velocity at the top of the roughness and the roughness height. That such a roughness Reynolds number should afford a basis for correlation is founded on the concept that for geometrically similar projections immersed in the linear portion of the variation of boundary-layer velocity with distance from the surface, discrete disturbances form at the roughness particles when the local Reynolds number of the flow about the roughness reaches a critical value. The critical value of this roughness Reynolds number for the roughness of reference 1 was found to be approximately 600. The results of the present investigation at supersonic speeds for the model surface at equilibrium temperature are summarized in figure 6 in the form of a plot of $\sqrt{R_{k,t}}$ against roughness location for the various roughness sizes tested. The square root of the roughness Reynolds number was chosen as the variable inasmuch as the value $\sqrt{R_{k,t}}$ is more nearly proportional to the critical projection height than $R_{k,t}$ for the projection submerged in the linear portion of the boundary-layer velocity profile. At supersonic speeds, where a variation of density and viscosity as well as velocity exists through the boundary layer the exponent of $R_{k,t}$ for linearity with k is even smaller than $\frac{1}{2}$. In order to consider the effect of Mach number on the boundary-layer density and viscosity, the values of the roughness parameter $\sqrt{R_{k,t}}$ for the supersonic results were obtained with the use of kinematic viscosity based on conditions at the top of the projection as well as the height of the projection and the velocity at the particle height. The particles of maximum height measured in each roughness strip (as presented in the table in the section entitled "Apparatus and Tests") were used for determination of the critical roughness Reynolds numbers. The velocity and temperature distributions through the boundary layer used in the computation of $\sqrt{R_{k,t}}$ were calculated by the methods of reference 13 corrected from the flat plate to the cone conditions by Mangler's transformation. For these calculations, the experimental longitudinal distribution of surface temperature was approximated with a polynomial, as suggested in reference 13. It is apparent from figure 6 that approximately the same value of the roughness parameter $\sqrt{R_{k,t}}$ as determined in reference 1 can be used, for practical purposes, to predict the initiation

of turbulence caused by distributed three-dimensional roughness at supersonic speeds at least up to a Mach number of 2 when the value of $\sqrt{R_{k,t}}$ is based on the local density and viscosity as well as the local velocity at the roughness height. It seems reasonable to expect that the same transition phenomenon and approximate critical value of roughness Reynolds number would be applicable for further moderate increases in the value of supersonic Mach number.

The effect of surface cooling in the presence of roughness on boundary-layer transition is shown in figure 7 by a comparison of the hot-wire traces observed for the cone surfaces at equilibrium temperature and for the cone surfaces cooled as indicated in figure 8. It was clearly demonstrated that when the roughness Reynolds number was just critical, that is, when turbulent spots began to appear with the surface at equilibrium temperature, cooling the cone surface resulted in a completely turbulent boundary layer. In fact, for the cooled condition it was necessary to decrease appreciably the tunnel unit Reynolds number in order to return the boundary layer to the laminar condition. Associated with the surface cooling for given values of roughness size, stream Reynolds number, and Mach number is an increase in roughness Reynolds number R_k caused by an increase in velocity at the top of the particle due to a thinning of the boundary layer and an increase in convexity of the velocity profile as well as an increase in local density and a decrease in local viscosity due to the lowered boundary-layer temperature. The fact that transition resulted from this increase in roughness Reynolds number indicates that the critical value of roughness Reynolds number was not increased to any important extent by the theoretical increase in laminar boundary-layer stability to small disturbances resulting from the surface cooling. This conclusion is verified by the close agreement in the values of $\sqrt{R_{k,t}}$ presented in figure 6 for the cooled model and for the model with the surface at equilibrium temperature and is consistent with reference 10 where it was shown that a laminar boundary layer made stable to vanishingly small disturbances by means of continuous suction was less sensitive to the finite three-dimensional type of surface disturbance only to a minor degree. The present results also offer a most plausible explanation for the reversal in the trend of increasing transition Reynolds number with increased cooling that was noted in references 6, 9, and 14.

CONCLUSIONS

An investigation in the Langley 4- by 4-foot supersonic pressure tunnel to determine the effect of distributed granular-type roughness submerged in the laminar boundary layer on boundary-layer transition at

supersonic speeds with and without surface cooling indicates the following conclusions:

1. The transition-triggering mechanism of distributed three-dimensional particles appears to be the same at supersonic speeds as that previously observed at subsonic speeds.

2. The value of the three-dimensional roughness Reynolds number parameter $\sqrt{R_{k,t}}$ at which turbulent "spots" begin to appear behind the roughness is approximately the same at supersonic and subsonic speeds when the roughness Reynolds number is based on the local values of density and viscosity as well as velocity at the top of the roughness and the roughness height.

3. For three-dimensional roughness at a Reynolds number less than its critical value, the roughness introduces no disturbances of sufficient magnitude to influence transition.

4. The critical three-dimensional roughness Reynolds number is not increased to any important extent by increasing the laminar boundary-layer stability to small disturbances through the use of surface cooling. For a given stream Mach number and Reynolds number, then, surface cooling will promote transition due to existing three-dimensional roughness inasmuch as the actual value of roughness Reynolds number is increased by the effect of cooling on boundary-layer thickness, density, and viscosity.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 2, 1958.

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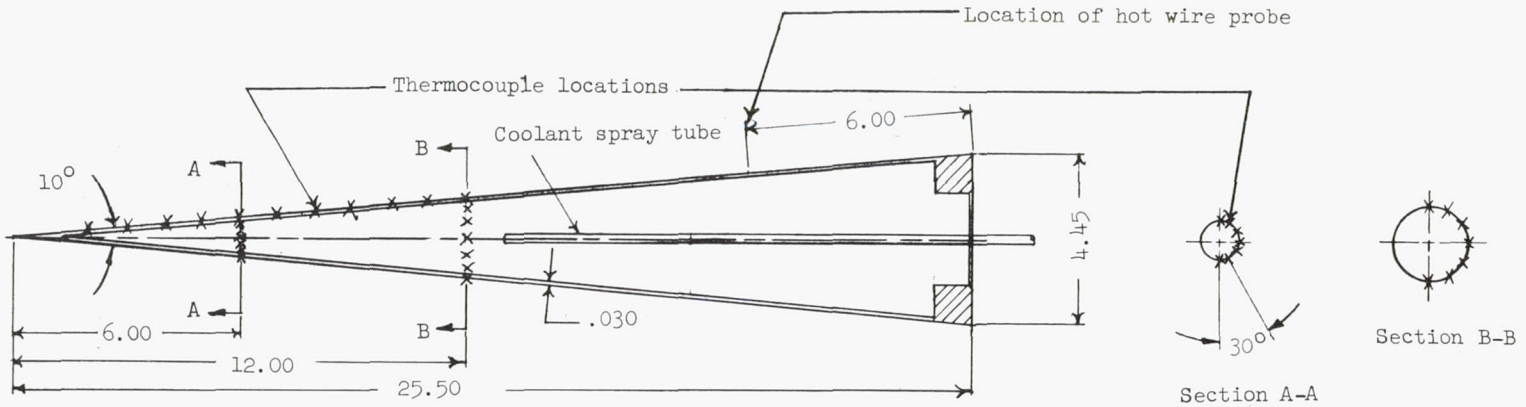
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Thermocouple locations, surface distance
2.008
3.011
4.015
5.019
6.022
7.026
8.031
9.034
10.038
11.041
12.045

Figure 1.- Sketch of hollow 10° cone used for cooling tests. All dimensions in inches.

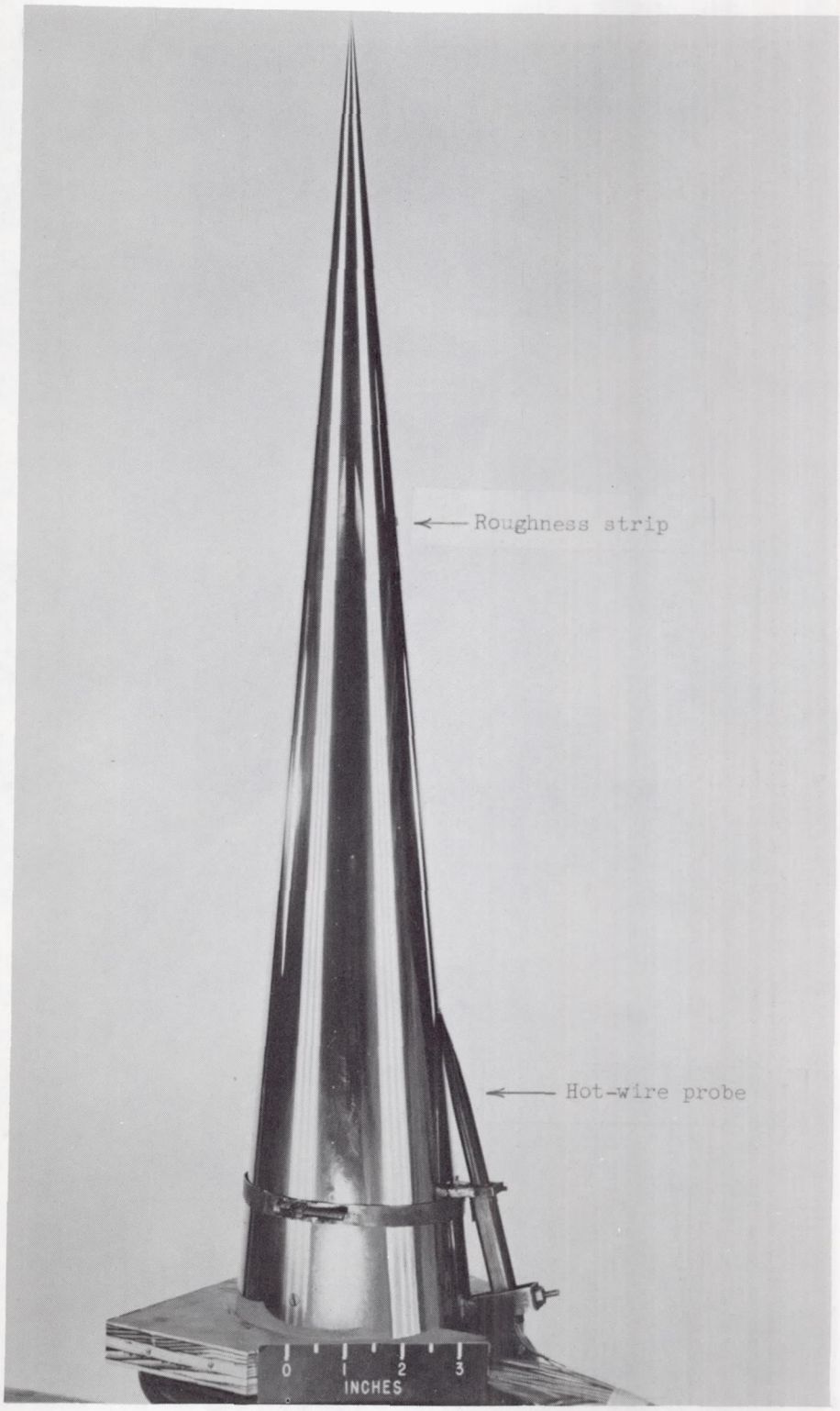
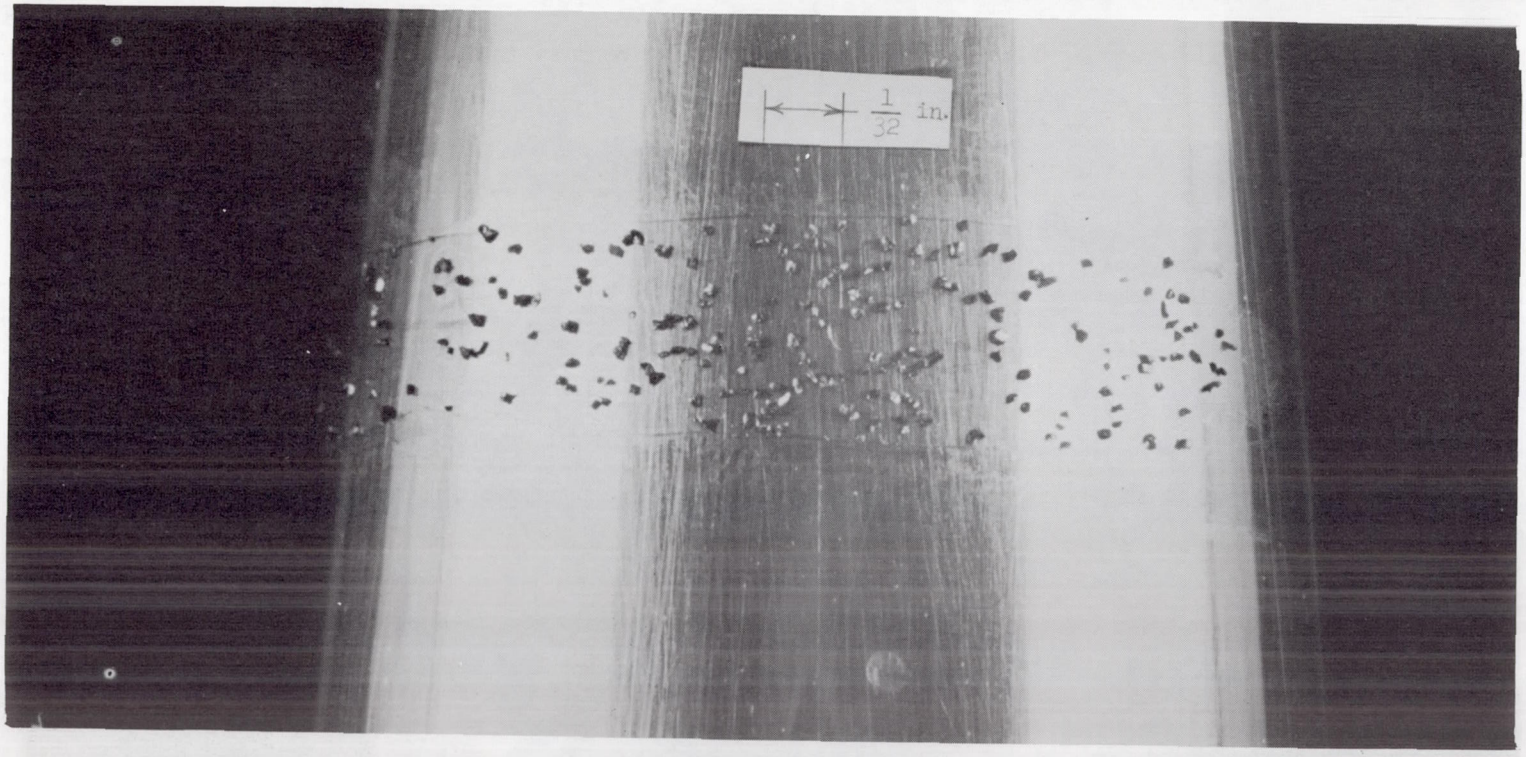


Figure 2.- Photograph of $25\frac{1}{2}$ - inch-long 10° cone model. L-57-4943.1



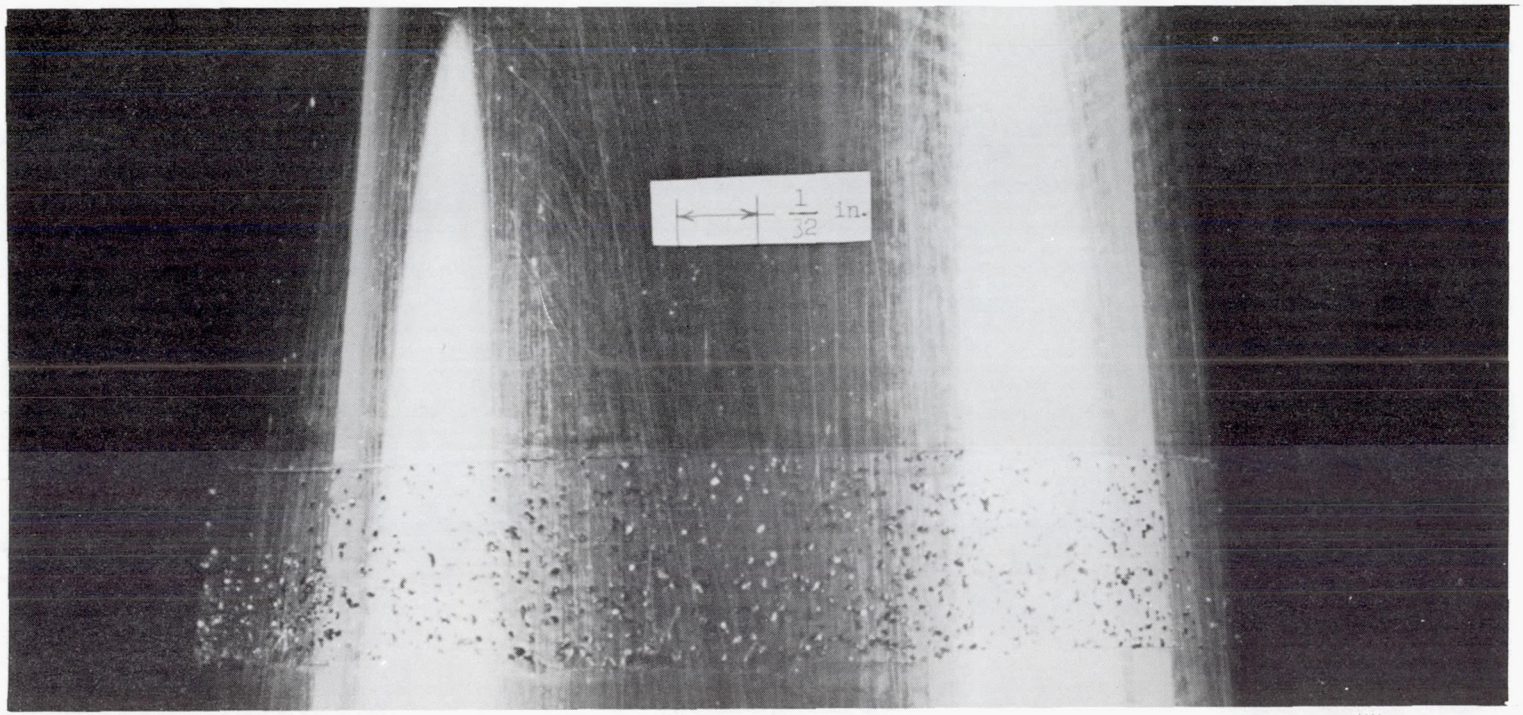
(a) Carborundum grit No. 60. L-57-4944.1

Figure 3.- Closeup photographs of representative strips of distributed granular-type roughness.



(b) Carborundum grit No. 80. L-57-4945.1

Figure 3.- Continued.



(c) Carborundum grit No. 180. L-57-4946.1

Figure 3.- Concluded.

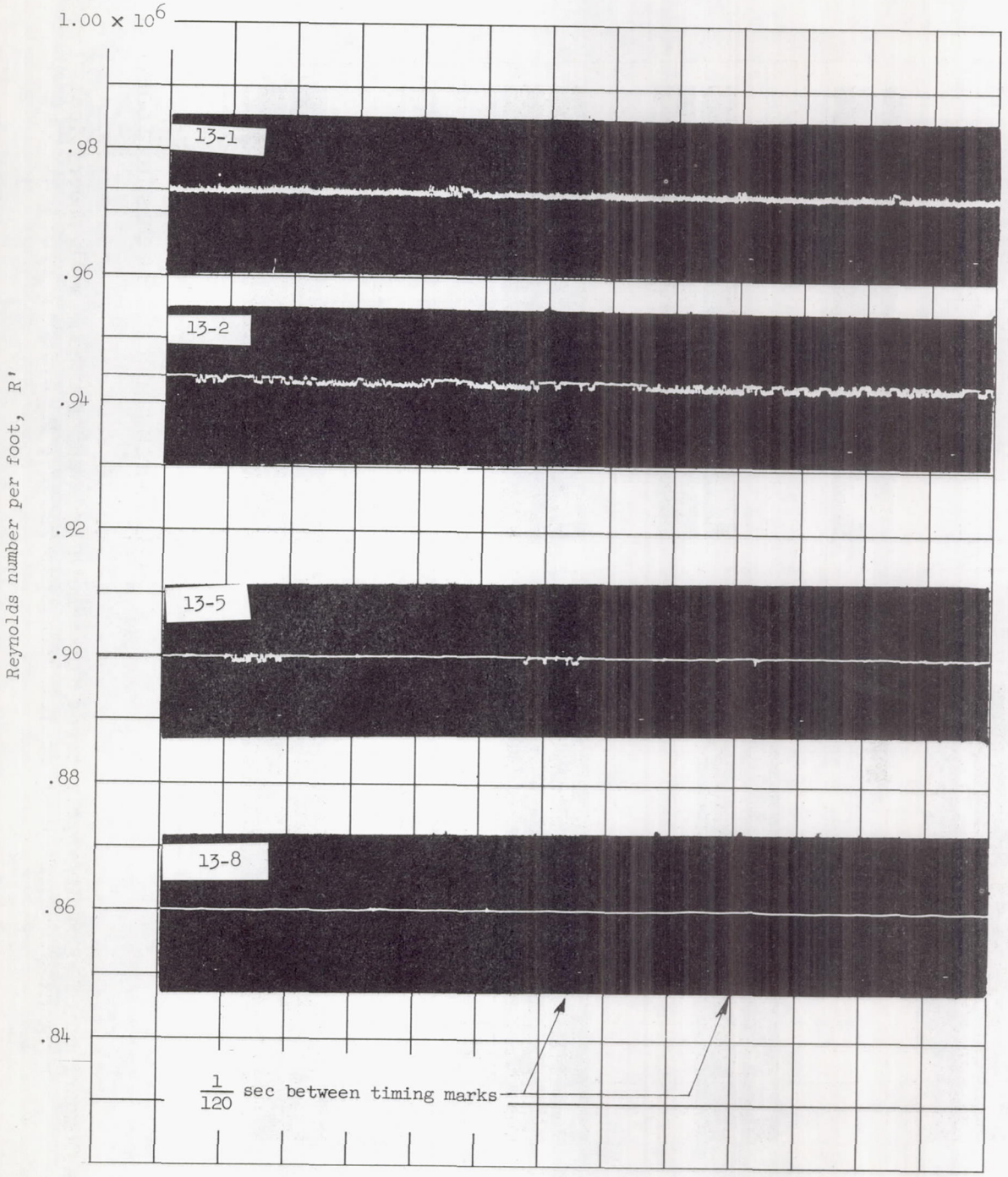


Figure 4.- Typical examples of oscillograph records through transition Reynolds number range. 0.017-inch roughness at 12.5 inches from apex; $M_\infty = 1.61$.

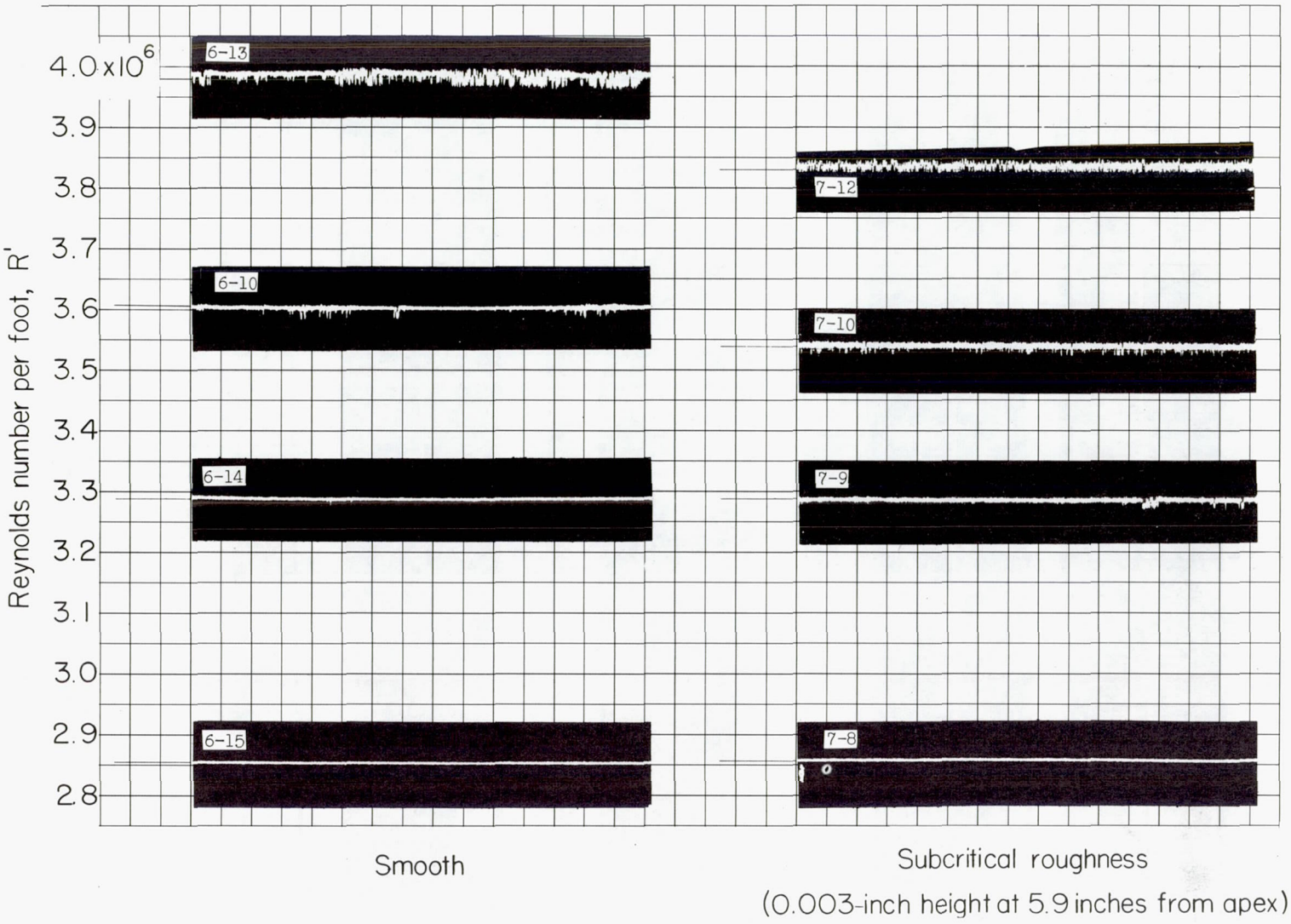


Figure 5.- Comparison of oscillograph records for smooth cone and for cone with subcritical roughness. Surface at equilibrium temperature; M_∞ = 2.01.

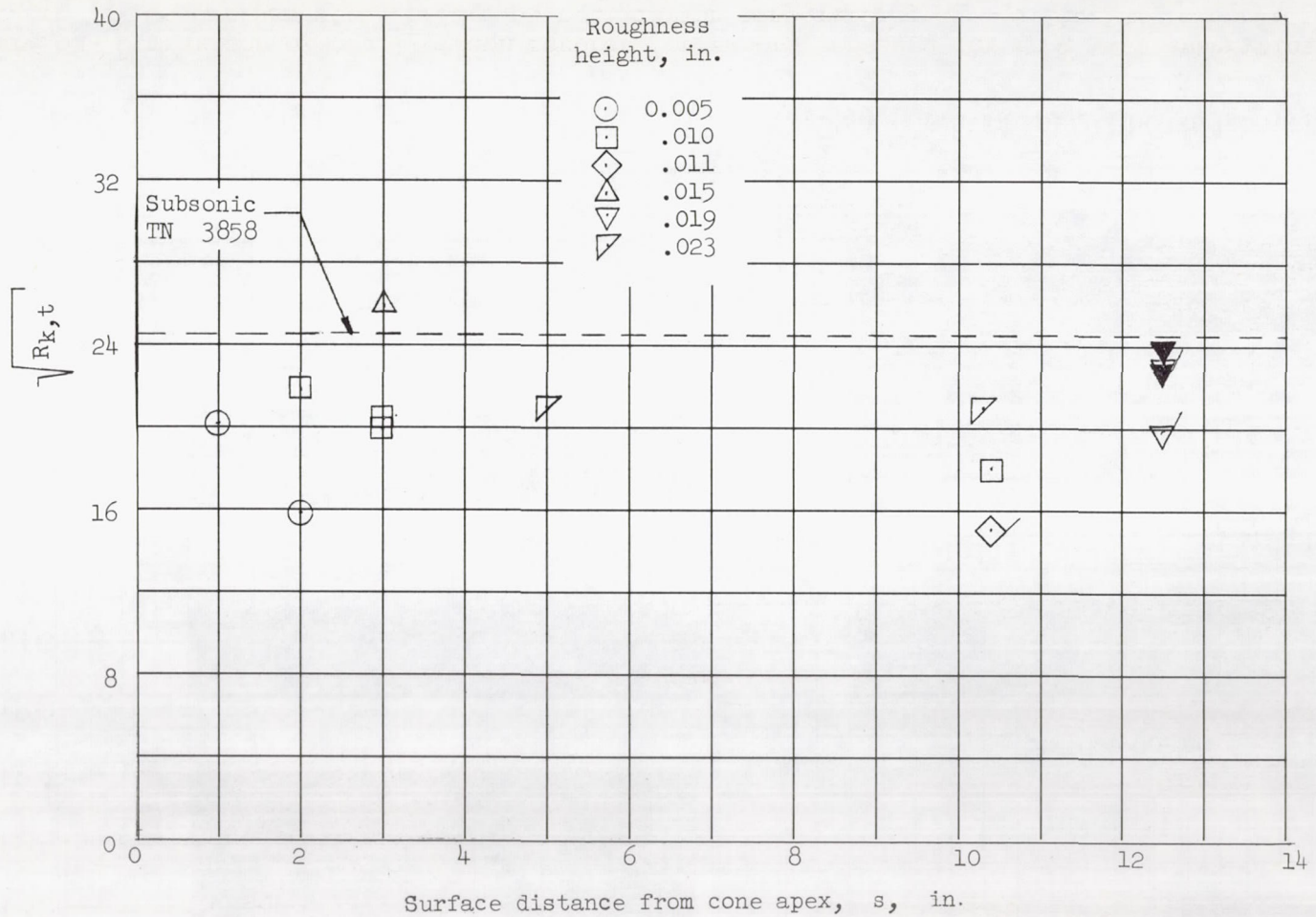
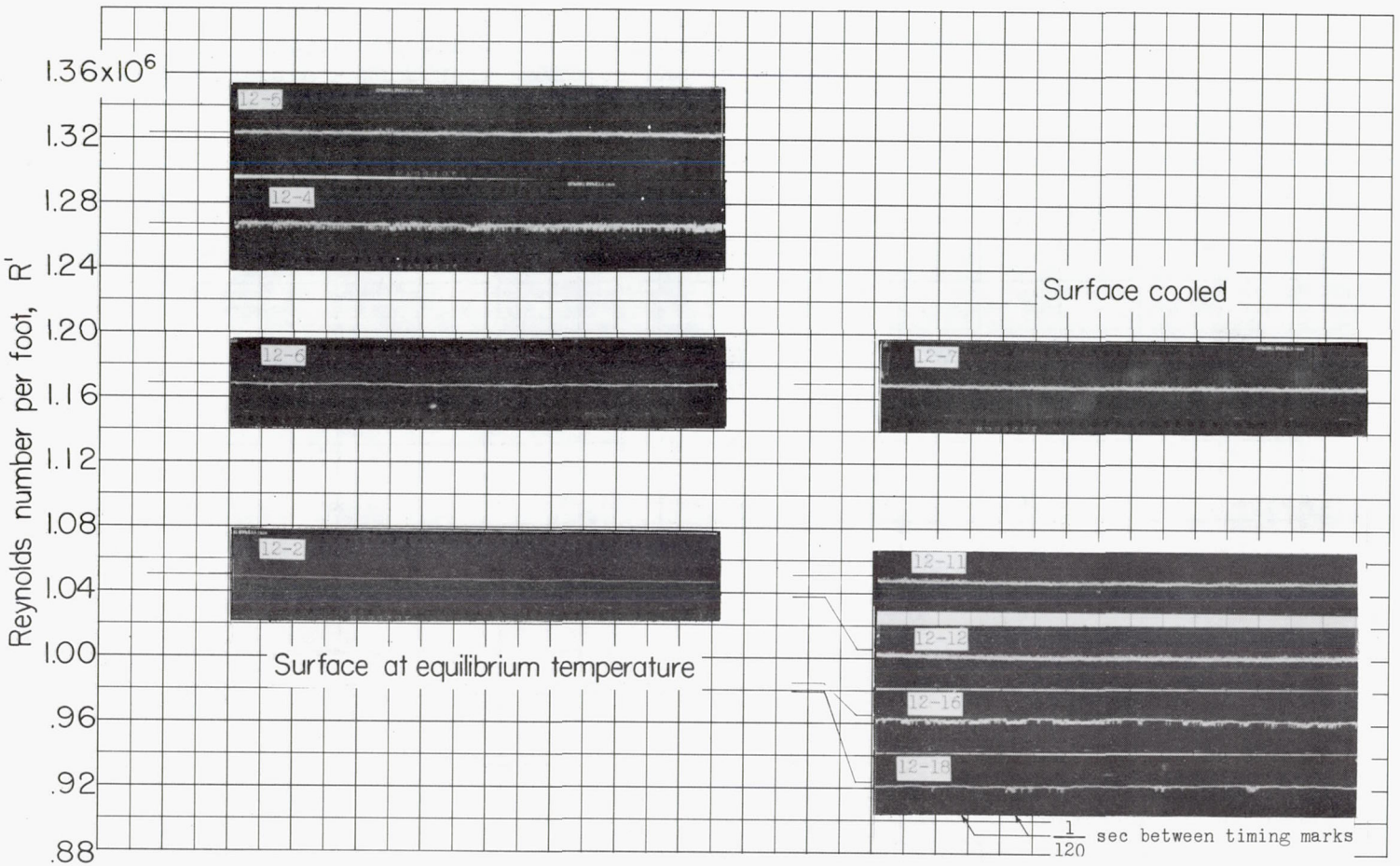
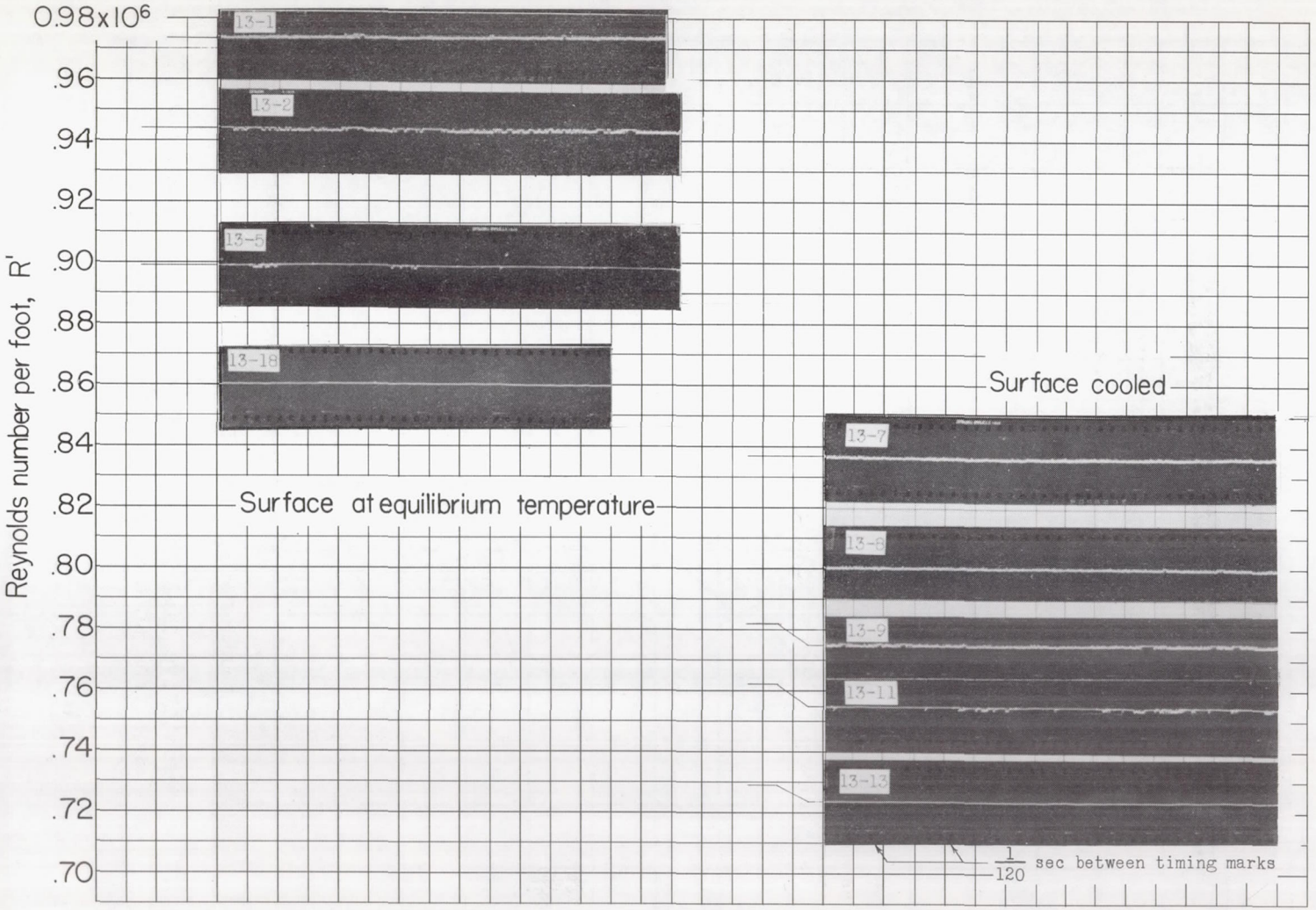


Figure 6.- Roughness Reynolds number for transition on 10° cone as a function of roughness location for surface at equilibrium temperature at $M_\infty = 2.01$. Flagged symbols denote $M_\infty = 1.61$; solid symbols denote cooled surface.



(a) $M_\infty = 2.01$.

Figure 7.- Comparison of oscillograph records for cone surface at equilibrium temperature and for cone surface cooled. 0.017-inch roughness at 12.5 inches from apex.



(b) $M_\infty = 1.61$.

Figure 7.- Concluded.

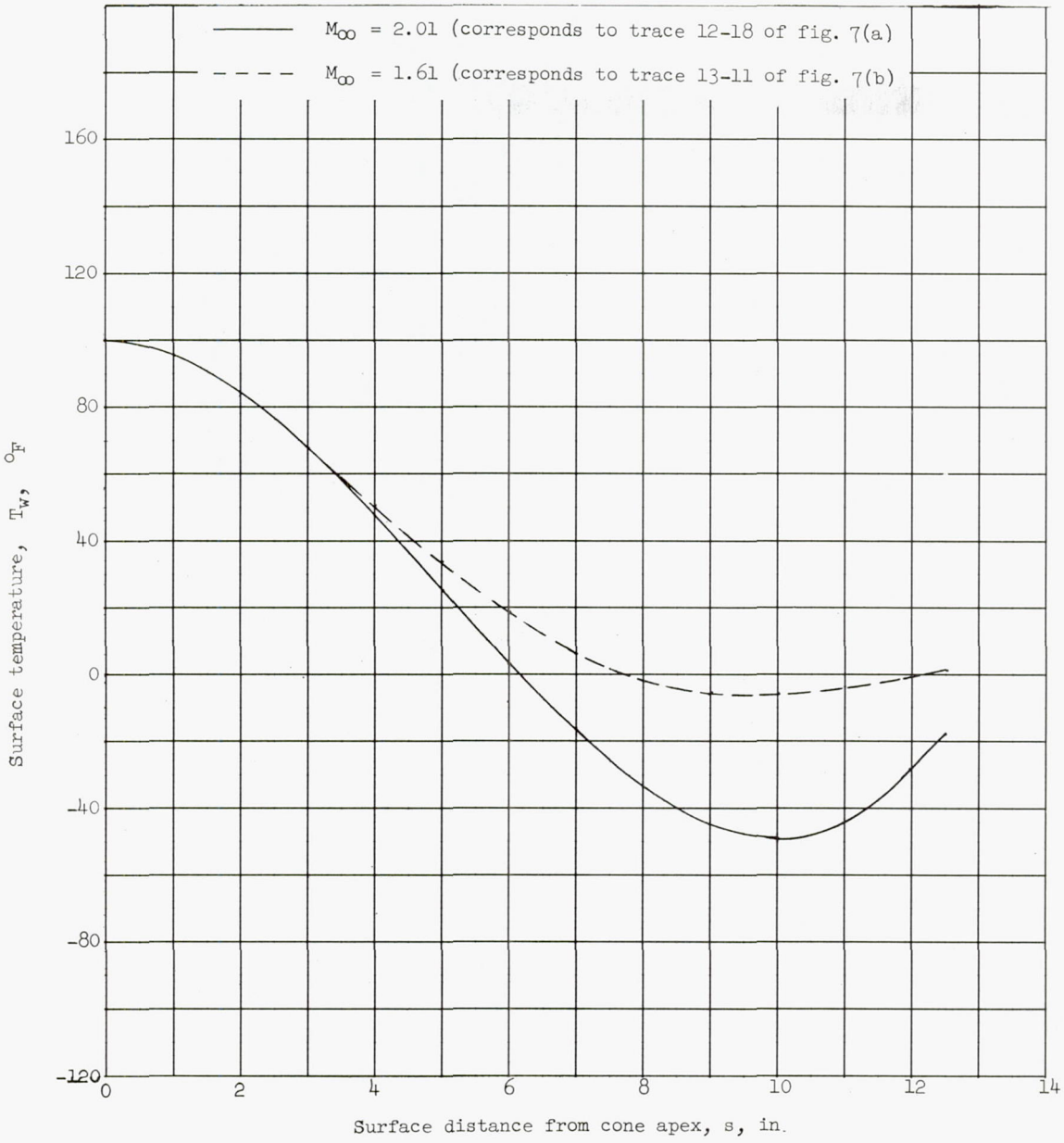


Figure 8.- Representative distributions of surface temperature with distance from cone apex for cooled condition.